Human Factors Research Needs for In-Time Aviation Safety Management Systems (IASMS) Design: Enabling the NASA "Sky for All" Future Airspace Vision

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Integrated safety management will be paramount for safely enabling the envisioned transformations of the future National Airspace System. Addressing the increasing need for advanced data analytics and fusion of aviation safety data, managed by human decision-makers, is essential for realizing the vision. The proposal, if accepted, will discuss safety management system challenges and how the concept of In-time Aviation Safety Management Systems addresses the need. It will also discuss human factors challenges involved in future integrated safety management, including trust, over-reliance, human-optimized data visualization, human-autonomy teaming, training, communication and dissemination of data, situation awareness, task load, and accountability.

INTRODUCTION

As we move towards advanced transformations of the National Airspace System, such as the National Aeronautics and Space Administration (NASA) Advanced Air Mobility (AAM) initiative, it is important to consider future needs of integrated safety management. With the emergence of new aviation markets and the increasing autonomy of systems, the way in which humans interact with these systems will be a critical factor in design and operational in-time safety assurance. The increasing complexity of operations will necessitate new ways of managing flight information and how to identify, assess, and mitigate potential safety risks. The envisioned changes in future markets involve a diverse range of flying vehicles, from legacy conventional passenger jets and General Aviation aircraft to new entrants including commercial space launches and new electric vertical takeoff and landing (eVTOL) vehicles (MITRE, 2020). The rapidly evolving landscape presents new safety challenges, particularly with the frequent, short-duration flights of eVTOL vehicles in congested airspace in close proximity to traditional aircraft, including large transport category aircraft. To realize this vision, it is necessary to address the increasing need for increasingly autonomous advanced data analytics and fusion of aviation safety data, all while being managed by human decision-makers; A critical need addressed by the In-time Aviation Safety Management Systems (IASMS) concept of operation (Ellis, Krois, Koelling, Prinzel, Davies, and Mah, 2021).

The IASMS embodies several critical attributes that are essential to its success. Firstly, it integrates various sources of operational data to support predictive analytics through the fusion of machine learning and artificial intelligence. Secondly, it emphasizes in-time decision-making and execution, utilizing model-based system modeling to ensure optimal performance.

The IASMS also incorporates best practices in human-system integration, including the management of information and human-computer interaction through effective human interfaces. Additionally, it places a strong emphasis on safety intelligence and the ability to "learn from all operations." Successful implementation and application of IASMS will require the addition of "predictive" safety management" and also a deeper understanding of human contributions to safety, a concept rooted in the principles of Safety-II (Ellis, Krois, Koelling, Prinzel, Davies, Mah, and Infeld, 2021).

The present proposal, if accepted, will describe revolutionary future visions of the National Airspace System (NAS) and how safety will need to be equally transformative as the new operations and technologies being designed to enable the future of aviation. It will summarize the current state of aviation safety and safety management systems (SMS), currently only required for Part 121 airline operators but expected to be required for all operators in the future NAS. Finally, it will describe how the concept of IASMS evolves beyond today's SMS to provide for requisite "services, functions, and capabilities" (SFCs) that address identified safety concerns to include human factors design and operational challenges.

SAFETY MANAGEMENT SYSTEMS

The framework for Safety Management Systems (SMS) was established by the International Civil Aviation Organization (ICAO) (ICAO, 2016). According to ICAO, SMS constitutes a systematic approach to managing safety that encompasses the necessary organizational structures, accountability, responsibilities, policies, and procedures. The traditional State Safety Program (SSP) framework of SMS, as outlined in ICAO Annex 19 (2nd edition) and informed by ICAO Standards and Recommended Practices (SARPS), is comprised of four pillars:

(a) Safety Policy and Objectives, (b) Risk Management, (c) Safety Assurance, and (d) Safety Promotion. SARPS serve as the foundation for a safe global aviation system, and the SMS pillars are intended to help manage commercial aviation safety risks in coordination with aviation service providers. The ICAO Safety Management Manual (Document 9859) offers guidance on safety management principles and concepts, the SSP, and SMS implementation, with the goal of supporting the continued evolution of safety management and the SSP of each ICAO state, such as the Federal Aviation Administration (FAA), in accordance with the provisions of Annex 19 (ICAO, 2018). 14 CFR Part 5 of the Code of Federal Regulations mandates the implementation of SMS by Part 121 Aviation Service Providers (i.e., commercial air carriers). The regulation identifies the basic processes integral to an effective SMS but does not specify the means of compliance. The FAA provides guidance and methods for developing and implementing an SMS through Advisory Circular (AC) 120-92B, titled "Safety Management Systems for Aviation Service Providers." (FAA, 2015). FAA addresses ICAO SSP requirements in Order 8000.369C, National Policy: Safety Management System (2020).

Safety Management Systems are currently not required for other operators in the NAS. The FAA has a notice of SMS proposed rulemaking for Part 135 operators, which are cargo carriers with under 7.500 pounds of payload and revenue passenger-carrying operators using aircraft having a limited number of passenger seats. SMS is expected to also be required for all emerging Advanced Air Mobility operations. The proposal, if accepted, will describe the challenges and barriers to implementation of traditional SMS, which includes significant human factors design considerations, and how addressed by the IASMS.

INTEGRATED SAFETY MANAGEMENT

In the rapidly expanding NAS of today, the safety of design and operational assurance present major challenges as human interaction with increasingly autonomous systems becomes more complex. The growing intricacy of future operations will continue to involve human operators who must manage flight information through dynamic interfaces, allowing for in/real-time identification, evaluation, and resolution of safety concerns. NASA, together with FAA and other stakeholders, is exploring innovative technologies and concepts for how different types of operations (e.g., Air Taxi) can be scaled and harmoniously integrated as part of a future information-centric (circa 2035) and "Sky for All" (circa 2045) NAS (FAA, 2021; 2022; NASA, 2022).

A significant domain of interest with AAM is Urban Air Mobility (UAM), characterized by its unique and evolving airspace, vehicle, and operational features. In UAM, low altitude airspace is utilized for the operation of vehicles that transport passengers and cargo and may be restricted to flying in designated corridors linking vertiports for take-off and landing. Additionally, other prospective emerging concepts of operations, such as autonomous cargo, Upper Class E, Commercial Space Launch, single-pilot operations, and public use and emergency response small uncrewed vehicles, present novel safety risks with increased frequency of flights in close proximity, carrying both people and cargo, within more congested and operationally intricate airspace (National Academies, 2020).

The proposal, if accepted, will describe the FAA and NASA future NAS visions, with specific focus on potential safety critical challenges posed by envisioned new operations and integration into airspace with more traditional operators. Significant human factors challenges have been identified that will be described.

NEED TO EVOLVE SMS

The NAS is undergoing continuous transformation, driven by technological advancements, market forces, and emerging opportunities. The NAS is being reimagined in the NASA "Sky for All" and the FAA's 2035 vision concepts. The paramount priority in this evolution of aviation remains safety and overcoming the challenges and constraints in both design and operations is essential for its successful advancement. Today, the overarching SMS has provided significant benefits in reducing aviation accidents and incidents through reactive and proactive safety management. However, the envisioned future concepts of operation present new safety challenges, with a significant increase in the number of vehicles flying in closer proximity to other aircraft. This includes the potential for remotely piloted or automated systems to share the same airspace with crewed aircraft. As such, it is imperative that safety management evolve to provide for a predictive SMS capability that reflects these significant changes that will substantially increase complexity and challenges to assure safety in the future NAS.

A key limitation is that today's SMS is labor-intensive with humans collecting, integrating, and assessing diverse data from multiple systems having different capabilities and identified known and emergent risks up leveled through a series of operational safety teams for further review and analysis. The sequential process involves the correlation of findings from diverse data sources, which are then reviewed and analyzed by different operational safety teams before being brought to the attention of risk mitigation boards for decision-making.

Another key limitation of SMS is the limited ability to scale due in part to the complexities of data sources that are not easily integrated. The limitation hampers the development of predictive analytics and the use of machine learning algorithms to detect and model anomalies, precursors, and trends as well as emergent risks. This hinders the ability to quickly monitor, integrate, and assess large data sets in real-time, thus delaying the identification and mitigation of known and emergent risks. The ability to fuse and integrate these data is seminal to developing predictive analytics and use of Machine Learning (ML) to identify and model anomalies, precursors, and trends as well as detect emergent risk.

Overall, the shortfall with today's SMS is its inability to quickly monitor, integrate, and assess large data sets to identify known as well as emergent risks in-time so that contingencies can be determined, and mitigations implemented expeditiously; that is, an "in-time" capability. Given these limitations, the National Academies (National Academies, 2018) have recommended the

adoption of IASMS to ensure and assure the safety of the future National Airspace System (NAS). The new perspective is seen as critical to addressing the challenges and limitations of the current SMS and ensuring a safe and efficient NAS and is an integral part of the NASA and FAA future vision concepts.

The proposal, if accepted, will discuss SMS challenges and new safety capabilities needed to enable the FAA and NASA future NAS visions, with specific focus on risk assessment and safety assurance.

IASMS CONCEPT OF OPERATION

NASA has been engaged in the development of the IASMS Concept of Operation (ConOps), which draws upon conventional commercial and other aviation operations and scales in complexity to accommodate the advent of newly emerging and evolving operations. The IASMS ConOps was developed in support of NASA's Strategic Implementation Plan Thrust 5, entitled "In-Time System-Wide Safety Assurance," which endeavors to establish a proactive, adaptive in-time safety threat management system (NASA, 2019). The system features fully integrated threat detection and evaluation capabilities that provide reliable mechanisms for dynamic, multi-agent planning, evaluation, and execution of in-time risk mitigation in response to hazardous events.

Safety risks can stem from patterns in precursors, anomalies, and trends. These risks may manifest as validated concerns that are known to designers and operators and can be detected and mitigated by the safety assurance SFCs (i.e., "known knowns"). Emergent risks, on the other hand, may be unknown to both designers and operators (e.g., an unexpected and surprising situation) but can be understood, adapted to, and managed by the SFCs through the application of machine learning or artificial intelligence (i.e., "unknown knowns"). Additionally, there may be risks that are recognized by designers or operators but are outside the scope of detection and mitigation by the safety assurance SFCs ("known unknowns"). Lastly, there may be unforeseen risks that are not recognizable by designers, operators, or the safety assurance SFCs and await discovery ("unknown unknowns"). To support in-time integrated safety management, IASMS is empowered by high-level functions, namely Monitor, Assess, Mitigate, and Assure that encompass domain-specific safety monitoring and alerting tools, integrated predictive technologies with domain-level applications, and in-time safety threat management.

The IASMS concept is founded upon a comprehensive array of SFCs that work in conjunction to enable its dynamic Monitor-Assess-Mitigate-Assure functions, a unique feature of IASMS (Ellis, Krois, Mah, Koelling, Prinzel, Davies, & Infeld, 2021). A Service serves the purpose of preventing or containing hazards before they can cause harm. The emergence of hazards during the design or operational phases highlights the need for a Service to manage them. Services can be provided by the vehicle, Urban Air Mobility system, or other agents in the architecture. A Function denotes the action that is required of automation, automated systems, pilots, or other human operators. It integrates streams of information and data to determine the necessary steps and timing to prevent or contain

risks, as well as utilizing predictive analytics to project known and emerging trends from performance data. A Capability encompasses the utilization of technology, including sensors and models, to detect, validate, generate, and distribute information and data across network architectures, serving as the foundation for the Functions and Services (Young, Ancel, et al. 2020).

The proposal, if accepted, will provide more details on IASMS concept and specific application of SFCs requisite to enable the future aviation visions, to include the many significant advances that the IASMS offers to extend more traditional SMS as well as a scalable and interoperable safety management system solution for non-airline operators (e.g., m:N AAM operations).

HUMAN FACTORS CHALLENGES

The IASMS represents an advancement in the realm of tailored safety, interoperability across operational domains, risk management and in-time safety assurance, offering a level of scalability and responsiveness that significantly surpasses that of conventional SMS. In order to achieve a comprehensive approach to integrated risk safety management and assurance, the IASMS leverages system-wide data that are aggregated and integrated from disparate data architectures of different commercial airline operators and other stakeholders obtained through new or existing data portals (e.g., NASA Digital Information Platform; Aviation Safety Information Analysis and Sharing). This necessitates the implementation of common architectural standards to ensure consistent and compatible alerting and mitigation strategies, which is a current focus of NASA R&D.

One of the defining characteristics of the IASMS is its ability to support human operators in rapidly managing known operational risks through highly automated systems that seamlessly integrate SFCs across operator and federated architectures. These SFCs are distributed in the form of on-board systems, ground-based systems, and cloud digital information systems that employ digital twins for enhanced system reliability. These information systems gather, aggregate, fuse, model, and distribute the data utilized by IASMS functions.

All current and prospective operators in the NAS may be required to implement an SMS (NBAA, 2021) beyond the current requirements for Part 135 operators (e.g., International Standard for Business Aircraft Operators, 2002) and other existing NAS operators (e.g., commercial space launch). However, the implementation of the Info-Centric and Sky for All future NAS visions, including IASMS, also poses a number of potential human factors challenges that must be addressed in order to effectively manage the increasingly complex airspace of the future.

New Human Roles

The assignment of human roles is derived from the functions they undertake although optimal task delegation has historically not been adequately done. For example, Sheridan and Parasuraman's analysis of supervisory control revealed five

human functions, including pre-planning, observing the automation's implementation of the plan, and taking action to abort or assume control as necessary (Sheridan & Parasuraman, 2005). The IASMS adopts these functions in terms of monitoring, evaluating, and mitigating to handle safety risks, while the human operator can be seen as perceiving, evaluating, and responding/taking action to mitigate risks based on the human information processing model put forth by Wickens (Wickens, 2002; Wickens, Hollands, Banbury, & Parasuraman, 2015). As technology and operations evolve, the roles of human operators will change incrementally but eventually dramatically as compared to today's human roles for safety management. The challenge lies in determining the interfaces for human interaction with increasingly complex and reliable autonomous systems, as well as ensuring that information is at least minimally managed by humans to guarantee timely safety.

New Human Responsibilities

In the realm of future aviation, it is envisioned that human will continue to play a pivotal role in ensuring safety through constant, in-/real-time surveillance of operations and mitigating emerging risks. Yet, a significant challenge lies in the fact that the current certification and safety assurance protocols presume the presence of people (e.g., safety analysts, dispatchers, pilots, air traffic controllers, etc.) for operational safety. For instance, the shift from conventional vehicle handling to advanced automated/autonomous systems that are properly designed, resilient, and capable would necessitate a phased implementation of autonomy. This would involve a progression from the highly capable pilots of today to those who would operate simpler vehicles (such as "simplified vehicle operations" with one (m) human pilot operating multiple (N) number of vehicles (i.e., m:N) responsible for operational monitoring and contingency management. Another example could be highly automated vehicles with passengers who would be capable of acting during emergencies (with fail-safe control remote capability). To actualize this vision of AAM, it is imperative to undertake research and development in the realm of human factors, and to innovate safety surveillance and contingency management technologies. This includes considering the need to revise current human-system architectures and design utilizing Model-Based System Engineering/Human System Integration (e.g., Mbaye, Jones, Infeld, & Davies, 2022; NASA, 2021) and Human-Autonomy/-System Teaming (e.g., Holbrook, Prinzel, et al., 2020; Pritchett, Portman, & Nolan, 2018). These serve as paradigms for the design of the IASMS.

New Information Requirements

Future SMS data analysts will have a significantly greater volume of data available, but these will also be substantially more complex and highly integrated data streams based on ML/AI methods of data science. For example, AAM is envisioned to provide for what is currently identified as 16 information classes that will make it challenging for the human to process all the data, and even more challenging to uncover underlying safety threats and risk trends (Young, Ancel, et al., 2020). Human factors issues include operator proficiency, system bias, trustworthy decision support (when the system is based on hidden layers of ML/AI), automation transparency, alerting, data visualization, management of information, and other information requirements and changes. IASMS has developed SFCs to help support collaborative decision making through intuitive data fusion and dashboard integration and data portals.

Collaborative Decision Making and Safety Intelligence

The management of safety risk across diverse operational domains necessitates a profound integration between humans and systems in order to optimize the utilization of the escalating quantity of information exchanged. The IASMS is intended to analyze operational situations quickly and help inform decisions based on the accessible data through predictive or adaptive processes. As an illustration, flight deck-based technologies, such as Aircraft Health Monitoring Systems, will preeminently identify and mitigate unfavorable aircraft conditions, such as excessive energy during approach, prior to the occurrence of safety incidents; this is an example of an aircraft SFC that transmit data in-time to IASMS for analysis together with all other aircraft flying in the NAS. However, the large volume of data presents a challenge for the human analyst to comprehend and assimilate without the assistance of sophisticated algorithms for big data analysis. Therefore, a crucial aspect of human factors engineering is to design these systems in a manner that enables the human analyst to grasp the safety-critical data and make informed decisions, which will continue to remain the human's responsibility (note: fully automated safety assurance is a distant prospect for IASMS). This, however, necessitates the establishment of a shared framework for collaborative decision-making, where the system provides substantial support to the human analyst in providing safety intelligence and guiding decision-making. The trust of the human in the system, while avoiding over-reliance, as well as other human factors design and implementation considerations, including potential issues related to "use, misuse, disuse, and abuse," (Parasuraman & Riley, 1997) will be of paramount importance.

The proposal, if accepted, will examine common and unique human factors and human-system interaction challenges involved in future integrated safety management, such as trust, over-reliance/complacency, human optimized data visualization, training, communication and dissemination of data and analyses, situation awareness and mental model formulation and maintenance, saliency of indicators and knowledge of critical safety events, accountability, decision bias, monitoring and supervisory control, and other potential human factors considerations and/or problems that should be confronted early in design lifecycle of such systems.

CONCLUSIONS

To transform SMS to the IASMS to help enable the future aviation visions safely, integrated safety management will be a key need. The IASMS represents a solution to evolve SMS through monitor, assess, mitigate, and assure SFCs that include the ability to fuse and evaluate increasingly large, disparate sets of data to quickly (in-time) identify and mitigate risks and hazards in ever increasingly complex operations while

integrating process changes to advance safety intelligence. Human factors and human-system integration will be key design challenges, but also opportunities to help ensure that they are addressed early in the system design lifecycle.

The proposal, if accepted, complements previous papers describing IASMS specific to system requirements to aviation operational domains, such as Advanced Air Mobility (AAM) (e.g., Ellis, Krois, et al., 2021); space launch and reentry (e.g., Ellis, Prinzel, et al., 2021); upper Class E (e.g., Ellis, Prinzel, et al., 2023); Part 135 business and on-demand charter (e.g., Ellis, Prinzel, et al., 2022); and Part 121 commercial cargo and airline operations (e.g., Ellis, Prinzel, et al., 2022). It will conclude with set of human factors R&D needs and discussion of future directions and collaborative efforts underway with major airlines, international safety organizations (e.g., ICAO, Flight Safety Foundation), industry and trade groups, academia, and the FAA.

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